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Synthetic Fibers Used in Concrete

Synthetic Fiber Reinforcement for Concrete

by
D. Ludirdja
J.F. Young

Synthetic fibers are often added to concrete for crack control in concrete slab construction. The most widely available and used plastic fibers in construction are polypropylene and polyester. While polyester fibers are potentially susceptible to alkaline hydrolysis, no such adverse effects have been reported in the field.

Suppliers recommend addition of 0.1 percent by volume for cracking control. At these levels, concrete strengths are only marginally affected, although some postcracking strength and additional ductility is observed during flexural loading. The fresh concrete slump is only slightly reduced, while the tendency for segregation and bleeding may be reduced. At these levels, the use of synthetic fibers prevents plastic shrinkage cracking in concrete slabs during placement. Adding the same amount of synthetic fiber may not control drying shrinkage cracking in the hardened slab. The use of synthetic fibers should not substitute for usual precautions for preventing this condition, nor should fibers replace welded wire fabric if shrinkage control joints will be spaced further apart than recommended for reinforced slabs.

At current prices, using synthetic fiber reinforcement as secondary reinforcement in concrete slabs is cost effective compared to welded wire fabric when added at a level no greater than 0.1 percent by volume.



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FOREWORD

This study was performed for the U.S. Army Corps of Engineers, Huntsville Division, by the Engineering and Materials Division (FM), of the Infrastructure Laboratory (FL), of the U.S. Army Construction Engineering Research Laboratories (USACERL) under MIPR No. W31RY0E878, February 1989. The investigation was performed for USACERL by the Center for Cement Composite Materials, Department of Civil Engineering, University of Illinois at Urbana-Champaign (UIUC) under contract No. DACA88-38-D-0005-21, "Synthetic Fibers Used in Concrete." The contract monitor was John R. Hayes, CECER-FM. The technical monitor was Glenda Hodges, CEHND-ED-PM.

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SYNTHETIC FIBER REINFORCEMENT FOR CONCRETE

1 INTRODUCTION

Background

Fiber reinforcement of cement-based materials is not a new process. Commercial production of asbestos-reinforced cement building products has been a thriving industry since World War II. The early work by Goldfein (1963) on synthetic fibers in Portland cement led to a patent covering polyolefin fibers (e.g., polypropylene, polyethylene, nylon, polyvinyl chloride, etc.). Polyolefins are thermoplastics that are generally inexpensive, lightweight, tough, alkali resistant materials. More recently there has been renewed interest in using synthetic fibers to replace asbestos in prefabricated building products. Theoretical treatment of the principles of fiber reinforcement were developed and summarized by Hannant (1978).

The addition of fibers to concrete for cast-in-place applications is a more recent development; the use of steel fibers was first studied around 1963. Since then there has been much interest in the influence of steel and other fibers (glass, carbon, synthetic polymer, and natural fibers) on the properties of concrete used in construction. The Army has a substantial investment in slab-on-grade construction, a process used in the construction of industrial warehouses, commercial slabs, housing, pavements, driveways, and sidewalks. As a major user of reinforced concrete construction technologies, the U.S. Army Corps of Engineers may benefit from the improved economy and serviceability offered by fiber-reinforced concrete construction. However, before the Corps can begin using fiber-reinforced concrete, a study to review and evaluate the cost-effective use of synthetic fibers to improve the properties of concrete is needed.

Objectives

The objectives of this report are to evaluate the use of synthetic polymer fibers as reinforcement in concrete used for slab-on-grade construction, and to provide guidance for the use of synthetic fiber-reinforced concrete (SFRC) in such construction.

Approach

The study included a survey of the suppliers of plastic fiber materials and a review of the literature reporting the results of experimental and field use of fiber reinforcement in concrete construction. This study included an examination of the properties of plastic fiber material designed for concrete reinforcement and for other uses (Chapter 2), a review of the effects of the addition of concrete fibers upon the strength and performance of concrete slabs (Chapter 3), and inferences drawn from these studied effects regarding the effective and efficient use of plastic fiber reinforcement (Chapters 4 and 5).

Mode of Technology Transfer

It is recommended that an Engineer Technical Letter (ETL) be issued that summarizes the conclusions and recommendations of this report.

2 PROPERTIES OF SYNTHETIC FIBERS

Several different kinds of polymers have been investigated for their suitability for use in concrete (Table 1). Many of these fibers have been investigated in the laboratory but have not been evaluated in field applications. In evaluating fibers five aspects are of interest:

1. Mechanical properties of fiber
2. Physical properties of fibers
3. Chemical durability
4. Fiber geometry and dimension
5. Cost and availability.

Mechanical Properties

A fiber's mechanical properties determine its potential as a concrete-reinforcing material. Table 2 summarizes the properties of synthetic fibers used to reinforce concrete. Except for polyaramid (Kevlar) fibers, whose properties lie between glass and steel, synthetic fibers are characterized by low modulus of elasticity and high elongation (Figure 1). This behavior is typical of polymeric materials in general. Since the modulus of elasticity for most cementitious materials ranges from 15 to 30 MPa,* the relatively low modulus of the fibers means that high strength composites are not achievable with synthetic fibers. Their advantage lies in increasing such properties as strain capacity, toughness, and crack control, properties that are more important for slab construction than strength.

Table 1
Synthetic Polymers Used To Reinforce Concrete
and Other Cement-Based Products

General Type	Specific Polymers
Polyolefins (Polyalkanes)	Polyethylene Polypropylene Polyvinyl alcohol
Polyacrylics	Polyacrylonitrile
Polyamides	Nylon
Polyaramids	Kevlar*
Polyesters	Polyethylene terephthalate (PET)

* Kevlar is a registered trademark of Dupont de Nemours Co.,
1007 Market St., Wilmington, DE 19898

* A metric conversion table is included on p 28.

Table 2
Synthetic Fiber Properties

Fiber	Density (g/cm ³)	Melting Point (°C)	Maximum Service Temp (°C)	Glass Transition Temp (°C)	Tensile Properties		
					Ultimate Strength MPa	Elastic Modulus GPa	Ultimate Elongation (%)
Polyethylene	0.95	115	85-125	-120	500	5	—
Polypropylene	HM	137	85-135	-123	500	15-30	—
	LM	165	150	-27	600	7	21
Polyvinyl alcohol	HM			-27	600	15	—
			100	85	1500	30	—
Polyacrylic	1.26			100	600	10	13
Nylon	1.14	250	120	50	1000	6	10
Polyaramid	LM	235	300		3000	70	4
	HM		300		3000	130	2.5
Polyester	1.35	260	150	70	1100	10	24
Steel	7.90	1535	-600	—	700	200	7
Glass	2.70	>500	-500	—	1100	70	2.5

*LM = low modulus; HM = high modulus.

Physical Properties

Table 2 also gives the typical physical properties of synthetic fiber. The fibers are characterized by low density so that a relative low mass of fibers yields a high volume of fibers in concrete. Polymeric fibers are also very flexible; fiber breakage or mechanical distortion will not be a problem during concrete mixing.

The relatively low thermal stability of polymers could be a disadvantage. Melting points are generally below 300 °C but service temperatures are considerably lower, since the fibers start to soften and lose their tensile properties at temperatures considerably below the melting point. This behavior causes loss of reinforcing capabilities in structures exposed to high temperatures (e.g., in a fire), but in the case of slab-on-grade, normal environmental temperature fluctuations will not cause a problem. The glass transition temperature (T_g), which represents a change in consistency from rubbery to brittle as the temperature is lowered, should also be considered. In most cases, T_g lies well outside service temperature fluctuations, but if T_g lies just above maximum ambient temperature usually encountered in service, as in the case of nylon, solar heating could cause the temperature in a concrete slab to exceed T_g .

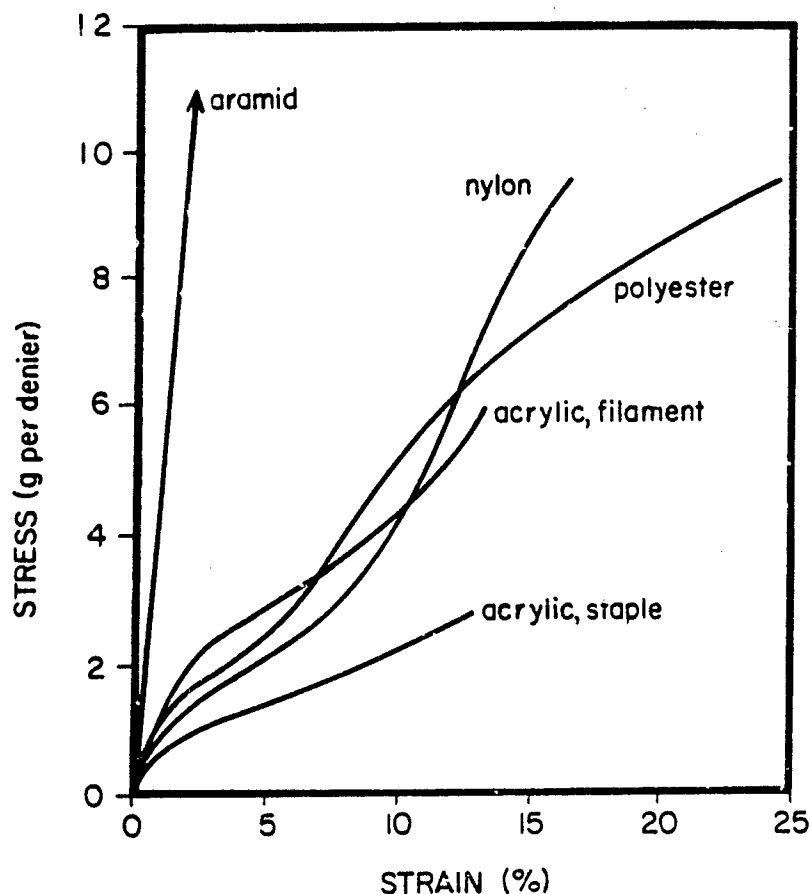


Figure 1. Tension Stress-Strain Curves for Synthetic Fibers.

Chemical Durability

Cement paste develops a moist alkaline environment detrimental to many organic materials. The minimum pH in a cement paste is about 12.3, which corresponds to a saturated calcium hydroxide solution. However, many modern cements have high alkali (sodium and potassium) contents, which can raise the pH to 13.5 or greater when the cement is mixed with water. This corresponds to about 0.6M sodium hydroxide (NaOH). This very high pH will be detrimental to some polymers. Polyesters, polyacrylics, and polyamides are particularly sensitive since they can undergo alkaline hydrolysis. Hydrolysis may be slow at room temperature, but may be significantly accelerated at higher temperatures. In studies on polyacrylic fibers only slight loss of strength at 20 °C was observed after 2 months, but a significant loss at 50 °C occurred in the same period (Wang, Backer, and Li 1987).

By contrast, the hydrophobic nature of polyethylene and polypropylene fibers makes them quite resistant to alkaline conditions. However, these fibers are sensitive to oxidation, particularly in the presence of sunlight, and are usually treated with anti-oxidants to reduce this susceptibility.

Fiber Geometry and Dimensions

Fibers are available in many different geometries and dimensions. Three different physical types of fibers are made commercially, although not all synthetic materials may be commercially available in each type.

Monofilaments

Monofilaments are single straight fibers usually made by drawing molten polymer. Such fibers are usually round in cross section, ranging in diameter from 50 μ m to 0.5 mm. Such fibers are usually strong since the drawing process tends to align the polymer chains and induce crystallization, but the smooth surface may result in a low interfacial bond strength, which limits the reinforcing capability of the fiber. However, bond strength is primarily determined by the nature of the polymer (Table 3). A hydrophobic polymer like polypropylene has a much lower bond strength than hydrophilic polymer like polyacrylics or polyaramids.

Table 3
Interfacial Bond Strengths for Synthetic Fibers

Fiber	Fiber Geometry	Shear Bond Strength (M)
Polypropylene	Monofilaments	0.7-1.2
	Rovings	0.1
	Fibrillated	0.2-0.4
Polyacrylic	Monofilaments	3-4
Polyester	Monofilaments	0.1-0.2
Polyamide (nylon)	Monofilaments	0.1-0.2
Polyaramid (Kevlar)	Rovings	3.8

Rovings (Tows)

Many polymers are spun in the form of filaments (fibrils) whose diameters vary from 5 to 15 μm in diameter. Several thousand fibrils are spun simultaneously, by drawing them from a single die and bundling together. The bundles are held intact either by a sizing material or by twisting them into yarn. Rovings are cut into short lengths (<2 in.) when adding them to concrete. In the concrete, the yarn separates into individual fibrils (Figure 2), which need to be dispersed efficiently during mixing. Dispersed rovings act as individual monofilaments within the cement matrix. The high surface-to-volume ratio should increase the effective interfacial bonding.

Sized rovings will not be penetrated extensively by the cement matrix during fabrication. However, it has been observed in the case of glass rovings that slow penetration of hydration produce into the bundle over time can cause the fibrils to bond together, thereby reducing the flexibility of the fiber. This phenomenon can severely reduce the reinforcing capabilities of such fibers. When this happens, "embrittlement" occurs: the composite progressively loses its strength and toughness, and gradually reverts to the properties of the unreinforced matrix.

Fibrillated Polymers

Fibrillated polymers are formed by splitting a polymer film longitudinally and then cutting it to suitable lengths and widths so that the fibers can be considered as bundles of crosslinked fibrils. When pulled apart, the fibrillated fiber opens out into a mesh of connected fibrils (Figure 3). The geometry of a fibrillated fiber can be described in terms of the film thickness (generally 15 to 100 μm) and the width of each fibril (100 to 600 μm). This form of fiber is limited to film-forming polymers (polypropylene and polyethylene). During mixing, the bundles are opened up by the aggregate to act as individual fibrils that each contribute to the reinforcing action. The fibers are easy to handle and to disperse uniformly within the concrete mix. Unsized rovings can be difficult to handle since they tend to disperse before being added to the mix; sized rovings do not readily disperse. Most fibrillated polypropylene fibers are treated with proprietary chemicals to improve wetting and dispersion of the fibers.

A slightly different fiber is the "pulltrusion" fiber, which is an extruded tape split mechanically into single rectangular fibers. The edges and ends of the fibers are frayed during the splitting to provide an enhanced mechanical bond.

Availability and Cost

A variety of commercial fibers is available within the United States; those specifically marketed for use in concrete are summarized in Table 4. While there are about 20 U.S. suppliers of fibers, Table 4 lists only those suppliers that distribute nationally or produce specialty fibers.

Because of the large supply, fiber costs have recently dropped. Prices range from \$2.35 to \$4.35 per lb, depending on the particular fiber and quantity purchased. There is no significant price difference between polyester and polypropylene although nylon fibers are presently a little more expensive. Many of these same fiber types are available in other countries. Table 5 lists synthetic fibers available overseas. For the most part these are designed for use in precast fiber-reinforced cement-based building products.

Some fibers (e.g., polyaramids [Kevlar] and polyamides [nylon]), are not manufactured specifically for use in concrete. Studies on reinforcing capabilities have used commercially available general purpose fibers not made specifically for use in concrete. DuPont de Nemours & Co. manufactures Kevlar fibers as well as polyester polyacrylic and nylon fibers, but does not sell these directly to the concrete industry. Other manufacturers (e.g., Amoco, Inc.) have similar policies.

*Amoco Chemical Co. (Subsidiary of Amoco Corp) 200 E. Randolph Dr., Box 87759, Chicago, IL 60640.



(a)



(b)

Figure 2. Separation of a Polypropylene Bundle in Concrete, (a) Before, and (b) After Mixing.

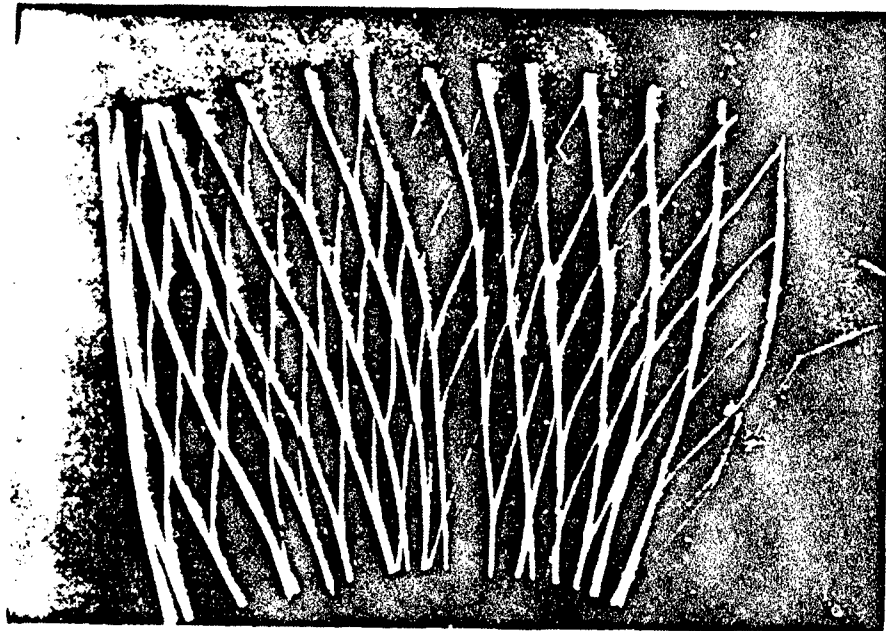


Figure 3. Expanded Fibrillated Polypropylene Fiber.

Table 4

**U.S. Suppliers of Commercially Available
Synthetic Fibers for Use in Concrete**

Fiber	Physical Form	Supplier
Polypropylene	Fibrillated	Fibermesh Co. 4019 Industry Drive Chattanooga, TN 37416 615/892-7243
	Fibrillated or monofilament Lengths: 3/4 to 2-1/2 in.	Forta Corp. 100 Forta Dr. Grove City, PA 16127 412/458-5221 800/245-0306
	Fibrillated Lengths: various	W.R. Grace & Co. Construction Products 62 Whittemore Ave. Cambridge MA 02140 617/876-1400
	Dispersible rovings Length: 3/4 in.	Euclid Chemical Co. 19218 Redwood Rd. Cleveland, OH 44110 216/531-9222 800/321-7628
	Dispersible rovings Length: 3/4 in.	Fiber-Lok, Inc. P.O. Box 1087 Keller, TX 76248 800/852-8889
Polyester	Dispersible rovings Length: 3/4 in.	Euclid Chemical Co.
	Dispersible rovings Length: 3/4 in. (or custom Length)	Fiber-Lok, Inc.
	Dispersible rovings Length: 1/4 to 2-1/2 in.	Hi-Tech Fibers P.O. Box 1638 Lexington, SC 29072 803/957-6963
Nylon	Monofilament Length: 3/4 in.	Nycon, Inc. Indianapolis, IN 317/842-7108

Table 5

Synthetic Fibers Produced Overseas

Fiber	Fiber Geometry	Application	Supplier
Polypropylene	Fibrillated	Concrete	Shell Chemical Co. (U.K.)
		Thin-sheet building components	Bridon Fibers and Plastics, Ltd. (U.K.)
	Extruded type ("Krenit")	Thin-sheet building components	Denmark
Polyethylene	Preformed monofilaments	Concrete	Mitsui Petroleum Chemical Industry Co. (Japan)
Polyaramid	Chopped fiber	Cement products	Teijin Ltd. (Japan)
Polyacrylic	Chopped fiber	Concrete Cement products	Hoechst AG (W. Germany)
Polyvinyl Alcohol	Chopped fiber	Cement products	Kurary Co. (Japan)

3 PHYSICAL EFFECTS OF SYNTHETIC FIBERS ON CONCRETE PROPERTIES

Type of Reinforcement

Synthetic fibers can be used as primary or secondary reinforcement for concrete slab-on-grade applications.

Primary Reinforcement

Synthetic fibers are usually used as primary reinforcement in thin sheet elements where conventional steel reinforcement is not feasible. The fiber contents must generally be greater than 5 percent by volume to provide adequate enhancement of flexural properties. These elements are prefabricated rather than cast-in-place. Theoretically, the enhancement of flexural strength of a random three dimensional fiber-reinforced brittle matrix composite can be calculated by the following equation (Hannant 1978):

$$\sigma_n = 2.44 \left(1 - \frac{l_c}{2l}\right) \sigma_{fu} V_f \quad [\text{Eq 1}]$$

where:

- σ_n is the flexural strength (modulus of rupture)
- l_c is the critical length of the fiber below which the fiber will pull out
- l is the length of the fiber
- σ_{fu} is the ultimate tensile strength of the fiber
- V_f is the volume fraction of the fiber in the composite

and

$$l_c = \frac{\sigma_{fu} r}{\tau} \quad [\text{Eq 2}]$$

where:

- r is the radius of the fiber
- τ is the interfacial shear bond strength between fiber and matrix. (Typical values for τ are given in Table 3.)

When $l < l_c$, Eq 1 reduces to:

$$\sigma_n = 2.44 V_f \tau \frac{l}{d} \quad [\text{Eq 3}]$$

where d is the diameter of the fiber and l/d is called the "aspect ratio."

For most synthetic fibers, l_c is very large, so that fibers (particularly monofilaments) will fail by pullout. For example, polypropylene monofilaments with a diameter of 50 μm will have $l_c = 30$ mm, polyester $l_c = 500$ mm, and polyacrylic $l_c = 10$ mm.

The low volume fraction of synthetic fibers used in slabs and the low interfacial bond strength do not greatly enhance σ_n , as calculated by equations 1 or 3. Most structural reinforcements have involved the use of steel or glass fibers, and more recently, carbon fibers. The development of high modulus synthetic fibers such as Kevlar (polyaramid) allows the possibility of replacing steel or glass, but at a high cost that makes current use of synthetic fibers for primary reinforcement for slabs on grade an infeasible alternative.

Secondary Reinforcement

Secondary reinforcement is used to control cracking caused by intrinsic tensile stresses such as drying shrinkage, plastic shrinkage, or temperature changes. For this purpose, the fiber content may be quite low, in the range of 0.1 to 0.3 percent by volume. This kind of reinforcement may be appropriate for slab-on-grade in combination with conventional reinforcing steel for structural reinforcement. In secondary reinforcement, fibers would replace welded wire mesh, which is used to control cracking in concrete due to dimensional instability.

The purpose of crack control is neither to eliminate cracking caused by intrinsic stresses, nor to increase the load-carrying capacity of the concrete; crack control replaces a random pattern of relatively large cracks with a more deliberately structured pattern of closely spaced, fine cracks. This in turn makes concrete less water permeable and hence more durable.

Effect of Fibers on Fresh Concrete

Workability

Bundled fibrillated polypropylene fibers tend to open up during mixing of concrete to create a dispersion of fine multifilament strands that are linked together with other fibrils. Chopped rovings disperse to individual microfilaments. The dispersion of such fine multifilament strands can reduce the flow (workability) of fresh concrete. This can affect a loss of slump, as shown in Table 6 and Figure 4 (Nagabhushanam, Ramakrishnam, and Vondran 1989; Hasaba, Kamakura, Koizumi, and Takemoto 1984). The length of fiber does not significantly affect slump.

This reduction in slump by the addition of synthetic fibers can increase the cohesiveness of concrete, improving the slip-forming characteristics of concrete and the stability of placements on steep inclines.

Dispersion of fibers during mixing is a concern in the production of fiber-reinforced concrete. Clumping or "balling" of fibers can be a problem at high fiber contents, but does not appear to be a major problem at additions below 1.0 percent. Synthetic fibers seem to perform better than glass or steel fibers in this respect.

Plastic shrinkage cracking is caused by excessive loss of water from fresh concrete due to evaporation. The problem is most acute in the placement of slabs and flatwork in the summer months when weather conditions may increase the rate of evaporation of moisture so that it exceeds the rate of bleeding. When this happens, local drying at the surface will result in plastic shrinkage cracking. It is not always easy to predict when plastic shrinkage cracking will occur, despite the availability of control charts, and once it has occurred, the problem is not easily corrected. Because the magnitude of tensile stresses needed to cause cracking is quite low, synthetic fibers have the potential to prevent this type of cracking in cases where inadequate preventive measures have been taken.

Zollo and Itler (1986) conducted a laboratory study on polypropylene fibers in concrete and reported a considerable reduction in plastic shrinkage cracking (-25 percent) when about 0.3 percent by volume of fiber was added. They also pointed out that network fibers can stabilize the matrix, prevent segregation

Table 6
Influence of Polypropylene Fibers on
the Properties of Fresh Concrete

Series	Fiber Content (%)	Initial Slump (in.)	Concrete Temp. (°F)	Vebe Time (sec)	Fiber Content
I	0	9.25	71.42	0.7	5.2
	0.1	8.25	70.16	2.0	9.0
	0.1	6.25	79.88	2.0	4.4
	0.5	5.25	70.88	3.5	5.4
	0.5	3.75	77.72	3.7	3.2
	1.0	0.13	69.98	10.0	4.4
	1.0	0.13	77.18	9.5	3.2
	1.0	0.13	77.18	9.5	3.2
II	0	3.75	80.06	2.2	5.2
	0.1	1.25	79.32	5.5	3.5
	1.0	3.13	80.24	3.7	6.9
III	0	6.25	80.96	1.6	4.3
	0.5	6.50	80.78	1.5	7.6

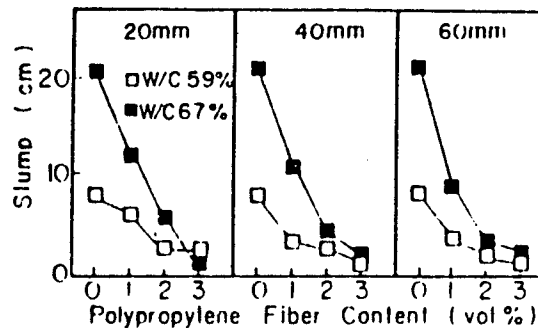


Figure 4. Relationship Between Slump and Fiber Content; W/C = Water/Cement Ratio.

and minimize bleeding. Kraai (1985) reported a similar reduction in the extent of cracking, but added that different types of polypropylene fibers may result in different improvements in plastic shrinkage cracking of concrete.

Studies sponsored by the Fibermesh Company (1987) also agree. Cracking in a control slab without any fiber started at 2.5 hours and developed most of the cracking pattern at 4 hours. After 24 hours, the slab that contained fibrillated polypropylene fiber had virtually no cracking (Figure 5).

Laboratory studies show that slabs with fiber reinforcement develop less plastic shrinkage cracking than slabs of control concrete. However, some field studies dispute this claim. Malisch (1986a, 1986b) conducted a field survey on the performance of polypropylene-reinforced concrete and concluded that there was not enough data to show that adding polypropylene fibers to concrete reduces plastic shrinkage cracking.

Tensile Strength and Compressive Strength

There is some disagreement in the literature concerning the effects of adding synthetic fibers on the tensile and compressive strength of concrete. Some studies have shown no significant improvements in tensile or compressive strengths when low volumes of polypropylene fibers are added to concrete (Hasaba et al. 1984; Zollo 1984; Ramakrishnan, Gollapudi, and Zeller 1987). Other studies have shown a slight decrease (<10 percent) in compressive strength over control specimens (Wiss, Janney, and Elstner 1985; Simpson 1988). These apparent differences are attributed to changes in the water-to-cement ratio between control and fiber-reinforced concrete. Since the addition of fibers slightly decreases slump, additional water is often used to bring the slump back into the desired range. This small addition (about 1 gal/cu yd) is sufficient to lower strengths by about 10 percent.

Flexural Strength

Flexural strength is a more important property than tensile or compressive strength, since it is used in the design of slabs. The theoretical influence of fiber reinforcement on flexural strength (modulus of rupture) was summarized in Equation 3. Flexural behavior has been examined experimentally by a number of groups.

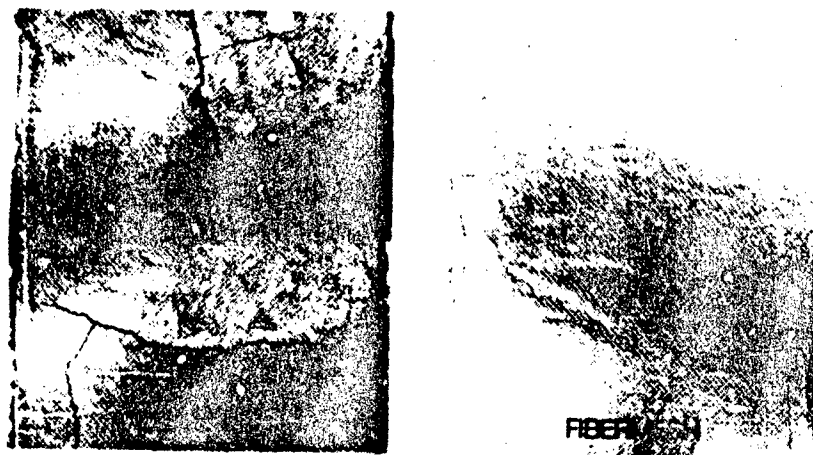


Figure 5. Comparison of Plastic Shrinkage Cracking in a Test Slab With and Without Fibers.

Small Samples. Several studies (Hasaba et al. 1984, Zollo, and Wiss, Janney, and Elstner Assoc. 1985) reported greater static flexural strength in concrete with added polypropylene fibers than in unreinforced concrete, especially when the specimens were cured in air. However, these increases were quite small when fiber contents were low. They can be attributed to the fibers' slowing crack propagation during loading through progressive debonding. It appears that, when compressive strength is used to estimate flexural strength, the relationship used for unreinforced concrete will still apply. Figure 6 shows load-deflection curves for tests of 4 x 4 x 14-in. concrete beams, tested in flexive (third point) loading according to ASTM C 1018. The test used concrete reinforced with different amounts of polypropylene fiber at 0, 0.1, 0.5, and 1 percent by volume (Nagabhushanam et al. 1989). Figure 6 shows that there is no change in the limit of proportionality at these levels of addition. Catastrophic failures of the matrix are observed once the limit is reached when the sustaining loads are carried by the fibers.

Large Slabs. Wiss, Janney and Elstner Assoc. reported slightly greater flexural strength in slabs (10 ft x 10 ft x 6 in.) containing polypropylene fibers (1.5 lb/cu yd) than in unreinforced concrete or in concrete containing welded wire fabric (Figure 7). Note that the wire fabric was 6 in. x 6 in., and the wire diameter was 1.4 mm x 1.4 mm, placed 2 in. below the surface of the slab. Since the fabric was not in the tensile zone, no effect on flexural strength would be expected.

Toughness

As discussed earlier, fiber-reinforced concrete is more ductile than unreinforced concrete. One way to quantify the increase in ductility is to measure the area under the load-deflection curve, which is defined as toughness. According to ASTM C 1018-89, the relative value of toughness (toughness index) can be calculated by measuring the area of load-deflection curve (three point bending) under certain deflections divided by the area under the load-deflection curve of first crack deflection. Figure 8 illustrates three toughness indices defined as:

$$I_5 = \frac{\text{AreaOACD}}{\text{AreaOAB}} \quad [\text{Eq 4}]$$

$$I_{10} = \frac{\text{AreaOAEF}}{\text{AreaOAB}} \quad [\text{Eq 5}]$$

$$I_{30} = \frac{\text{AreaOAGH}}{\text{AreaOAB}} \quad [\text{Eq 6}]$$

For elastic-plastic materials $I_5 = 5$, $I_{10} = 10$ and $I_{30} = 30$. For brittle materials, $I_5 = I_{10} = I_{30} = 1$. Table 7 shows results for concrete reinforced with polypropylene fibers that show intermediate behavior.

Flexural Fatigue Strength

Nagabhushanam et al. (1989) conducted a study of the fatigue behavior of concrete reinforced with low volumes (<1.0 percent by volume) of polypropylene fibers subjected to sinusoidal waveforms of 20 cycles/sec. The endurance lower limit was 10 percent and maximum limit was 55 to 80 percent of maximum static flexural strength (nonreversible load). After fatigue loading, the specimens that survived were tested in static flexural loading. The results indicate that the fiber-reinforced specimens have higher fatigue strength and higher endurance limit for two million cycles. In general, the static flexural strength of fiber-reinforced concrete increased after being subjected to fatigue loading, a behavior also observed in unreinforced concrete (Neville 1981).

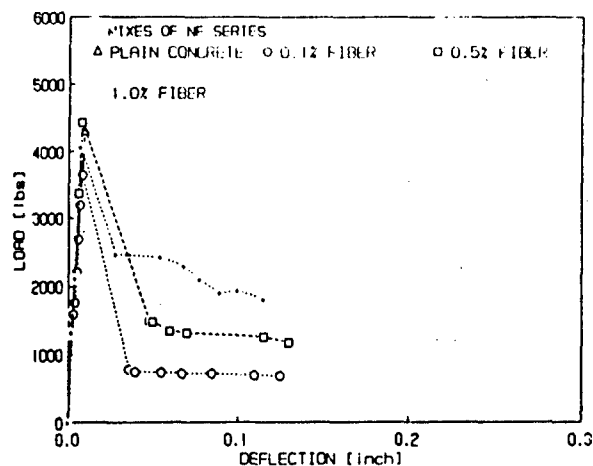


Figure 6. Load-Deflection Comparison Curves

Crack Control

Crack Spacing

Fiber-reinforced concrete is expected to have a finer crack pattern than plain concrete. The theoretical crack spacing (Hannant, Zonsveld, and Hughes 1978) is given by:

$$X = \frac{V_m}{V_f} \frac{\sigma_{mu} A_f}{\tau P_f} \quad [\text{Eq 7}]$$

where:

- X = minimum crack spacing
- V_m, V_f = matrix and fiber volume fractions, respectively, in the composite
- A_f, P_f = cross sectional area and perimeter of the fiber
- τ = interfacial shear bond strength
- σ_{mu} = the ultimate tensile strength of the matrix.

The crack spacing is directly related to the radius of the fiber for circular cross section, since:

$$\frac{A_f}{P_f} = \frac{r}{2} \quad [\text{Eq 8}]$$

The finer the fiber, the smaller the crack spacing. The other important factor in this equation is the interfacial bond strength. As discussed earlier, polypropylene fibers have lower values of shear bond than polyacrylic fibers (Table 3). This means that the latter can more effectively minimize the crack spacing at a given fiber content.

Cracking in Slabs

Most suppliers recommend short (3/4-in.) fibers at an addition rate of 1 lb/cu yd to control plastic shrinkage cracking, although longer fibers are available. Adding fibers for this purpose should not absolve the contractor from taking recommended precautions against plastic shrinkage. For control of drying

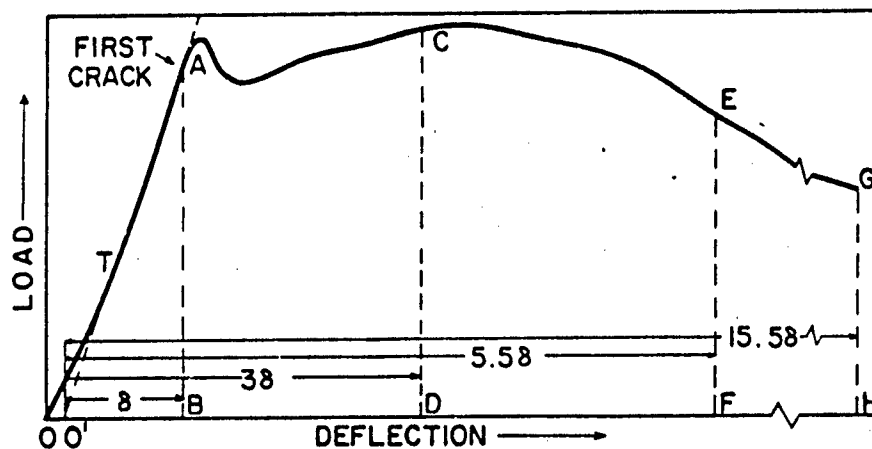


Figure 8. Analyses of Load-Deflection Curve According to ASTM C 1018.

shrinkage cracking in slabs-on-grade, a longer (i.e., 2-in.) fiber with a 1.5 to 1.6 lbs/cu yd (0.1 percent by volume) minimum should be used. The use of longer fibers is based on the theory that the crack spacing will be reduced as the anchored length increases the bond, provided that fibers do not break (Eq 4). The reduction in crack width as the crack spacing is reduced will give fiber-reinforced concrete lower water permeability than unreinforced concrete.

Joint Spacing

For unreinforced concrete slabs-on-grade, the recommended joint spacing in feet is typically two to three times the thickness of the slab in inches. Wider joint spacing is allowable when the concrete is reinforced with welded wire fabric. Joint spacing for concrete containing synthetic fibers should follow that of plain concrete (Vondran and Webster).

Table 7

Toughness Indices of Fiber-Reinforced Beams

Series	Fiber Content (%)	First Crack Toughness (in.-lb)	I_s	I_{10}	I_{30}	I_{10}/I_s	I_{30}/I_{10}
I	0	—	1.000	1.00	1.00	1.00	1.00
	0.1	17.28	3.519	5.11	9.00	1.47	1.76
	0.1	—	1.000	1.00	1.00	1.00	1.00
	0.5	24.65	3.330	5.32	11.99	1.60	2.30
	0.5	19.22	4.650	7.33	14.37	1.58	1.96
	1.0	19.79	3.510	6.53	16.49	1.87	2.53
	1.0	13.57	4.810	8.36	21.98	1.75	2.62
II	0	—	1.000	1.00	1.00	1.00	1.00
	0.1	23.39	4.120	5.59	9.13	1.35	1.64
	1.0	17.08	4.020	7.69	21.12	1.91	2.73
III	0	—	1.000	1.00	1.00	1.00	1.00
	0.5	14.86	3.510	6.23	16.06	1.78	2.58

4 EFFECTS OF EXPOSURE ON LONG-TERM DURABILITY

Alkaline Hydrolysis

As mentioned in Chapter 2, polyester, polyacrylics, and polyamides (nylon) can potentially undergo alkaline hydrolysis in the presence of the highly alkaline pore water ($\text{pH} > 12.5$) that exists in saturated concrete. How much this occurs in practice will depend on three factors :

1. The degree of saturation of the concrete
2. The rate hydrolysis will occur
3. The extent that hydrolysis will reduce the mechanical properties of the fiber.

Concrete slabs-on-grade will slowly dry out once curing has finished. At the top of a slab, the concrete will be approximately in equilibrium with the ambient humidity, while the lower part will be close to the equilibrium internal relative humidity (rh) attained in mass concrete (80 to 85 percent). Ambient external relative humidity ranges from 100 percent (after rain) to less than 20 percent in arid climates, and is typically 60 percent in areas within the eastern and southern United States. Thus it can be assumed that the mean relative humidity in a slab exposed to the weather will most likely lie in the range of 70 to 80 percent. Concrete floors in heated buildings will have a much lower mean relative humidity. Capillary pores down to 0.1 mm in diameter will be largely empty of water at 70 percent rh and hence the movement of water within the concrete is restricted. This will reduce the rate at which hydroxide ions can reach the surface of the fibers to initiate hydrolysis.

The rate of fiber degradation will thus be limited by diffusion through fine capillary pores (0.1 to 0.0025 mm) and micropores (< 0.0025 mm), and surface diffusion through films of adsorbed water on the walls of the larger pores. However, at the surface of exterior slabs, the potential exists for the upper 0.5 to 1.0 in. of the concrete to experience a higher degree of saturation and warmer temperatures during the summer months, leading to a higher rate of degradation. A gradual atmospheric carbonation of the concrete surface would offset this degradation by reducing alkalinity to a pH of less than 12.0.

However, unless hydrolysis advances to a point where the tensile properties of the fibers are significantly reduced, it need not adversely affect their reinforcing capabilities; failure usually occurs by pullout rather than by mechanical failure. Initial degradation of fiber-reinforced concrete composite would be accompanied not by a drop in ultimate compressive strength or modulus of rupture, but by a loss of toughness and crack control. Furthermore, if fibers are added for the purpose of controlling plastic shrinkage cracking, then degradation subsequent to curing would not be of major significance.

No controlled studies have been published that address the question of long-term performance in concrete of synthetic fibers susceptible to alkaline attack. However, neither are there reports of failure in the field due to such degradation. Thus, no definite assessment of long-term service performance is possible, although it is thought that, for normal applications, this would not be a serious drawback. If the concrete were to be subjected to prolonged conditions of high humidity, it would be advisable to use alkali-resistant synthetic fibers such as polypropylene or polyethylene.

Thermal Resistance

Synthetic fibers cannot withstand high temperatures. Most plastics soften and lose much of their tensile properties at temperatures in the range of 150 to 250 °C. The maximum ambient temperatures of external slabs do not rise high enough to cause a problem. Concrete floors in warehouses and other closed

facilities may be exposed to high temperatures during a fire, so that fibers would lose their properties and the slab would behave as unreinforced concrete; shrinkage cracking would then occur.

Oxidation

Polypropylene and polyethylene fibers can oxidize; however, this form of degradation would be confined only to the surface of the concrete slab. Furthermore, polypropylene fibers are usually treated with antioxidants, further reducing the danger of this form of degradation.

Abrasion Resistance

Polypropylene fibers have been reported to improve abrasion resistance.

5 A COMPARISON OF SYNTHETIC FIBER REINFORCEMENT WITH CONVENTIONAL WELDED WIRE FABRIC

Crack Control

One advantage that synthetic fiber reinforcement offers is its ability to control cracking caused by plastic and drying shrinkage. These fibers cannot be used to replace welded wire fabric to control cracking, but at the levels of addition recommended by fiber suppliers, they can eliminate plastic shrinkage cracking, which is not controlled by welded wire fabric.

Plastic Shrinkage Cracking

Two laboratory studies of plastic shrinkage in concrete found that adding polypropylene fibers prevented cracking. These tests were conducted under severe curing conditions, well demonstrating the ability of fibers to control this kind of cracking. Theoretically, this is to be expected since fresh concrete has a very low modulus of elasticity (acting only as a "quasi-solid") so that very small tensile stresses will cause cracking. Fibers limit cracking to fine cracks, which relieve tensile stresses and can self-heal during curing (Kraai 1985, Dahl 1985).

Drying Shrinkage Cracking

Drying shrinkage cracking is caused by restraining the volume reduction that accompanies loss of water from hardened concrete. The ability of synthetic fibers to control drying shrinkage cracking is less clear. Unrestrained shrinkage is not appreciably changed by the addition of fibers (Goeb 1989). In unreinforced slabs, the recommended joint spacing in feet is 2 to 3 times the slab thickness in inches; i.e., in a 6-in. slab, shrinkage control joints should be 12 to 18 ft apart. Welded mesh fabric is used to allow a larger spacing of control joints. Cracks that form between the control joints are kept closed by the wire mesh. Cracks with less than a 0.04-in. diameter allow load transfer to occur across the crack through aggregate interlock, and prevent faulting.

A survey of concrete slabs containing polypropylene fibers was conducted in 1986. Although no definitive conclusions could be made, the observations suggested that, when slabs had joint spacings greater than those recommended for plain concrete, cracking was likely to occur. Cracking should be expected at re-entrant corners. Bonded overlays were susceptible to cracking, even when welded wire fabric was also present. Since suppliers do not recommend increased joint spacings, it has to be concluded that the use of synthetic fibers at the recommended level of 0.1 percent by volume additions (1.5 lb/cu yd) cannot be considered a direct replacement for welded wire fabric. However, the use of fibers may help guard against cracks that may occur early in the life of concrete due to rapid drying or before control joints have been saved. Postcracking strength (Figure 7) may be sufficient to prevent faulting.

Cost Effectiveness

The cost of reinforced concrete varies within a determined range, expressed as the cost/sq ft for concrete (reinforced with either synthetic fiber or welded wire fabric) for a certain depth.

The cost of a welded wire fabric, reinforced, 6-in. concrete slab was \$0.06 in materials and \$0.03 in labor, for a total cost of \$0.09 per sq ft, independent of slab thickness from 4 to 8 in. (Simpson 1988).

The costs of synthetic fiber were obtained from several leading suppliers. Suppliers generally sell to ready-mix producers who then pass on the additional cost plus a markup to the contractor and hence the owner. If the contractor operates its own on-site batch plant, or if the owner (e.g., the Army) purchases the fibers directly, then the cost will be lower. Bulk purchases would further lower the cost. Currently the cost to the ready-mix supplier for 3/4-in. long fiber ranges from \$2.50 to \$3.50 per lb, for both polypropylene and polyester fibers. Longer fibers will cost about 30 percent more. Additions of 1.5 lb fiber/cu yd, would cost about \$0.01 to \$0.02 per sq ft per in. of depth. For a 6 in. thick slab, the cost ranges from \$0.06 to \$0.12. Additional labor costs are negligible. These figures represent an upper limit, so that it can be concluded that the use of synthetic fibers will be cost competitive with welded wire fabric when added at a level of 0.1 percent by volume. If higher volume fractions are used, the cost will no longer be competitive.

6 CONCLUSIONS AND RECOMMENDATIONS

This investigation has evaluated the use of synthetic polymers as reinforcement in concrete slab-on-grade construction and concludes that:

1. The addition of polypropylene fibers to concrete may prevent plastic shrinkage cracking, even under severe conditions.
2. The addition of polypropylene fibers to concrete that contains silica fume increased the abrasion resistance of the concrete in a simulated road test.
3. At present prices, synthetic fibers are cost effective as a secondary reinforcing material for concrete slabs when added at a level no greater than 0.1 percent by volume.
4. Since the low volume fraction of synthetic fibers used in concrete slabs and the low interfacial bond strengths of the fibers do not greatly enhance the flexural strength of the slab, the use of synthetic fibers is not a feasible alternative for primary reinforcement in concrete slabs. Moreover, since the volume fraction of synthetic fibers with the high modulus of elasticity required for primary structural reinforcement of concrete slabs would exceed the cost effective level of 0.1 percent by volume, it is not currently cost effective to use synthetic fibers as primary structural reinforcement for concrete slabs.

This study provides the following recommendations for the use of synthetic fiber in SFRC construction:

1. Synthetic fiber reinforcement for concrete slab-on-grade construction should not serve as a direct replacement for welded wire fabric, nor should synthetic fiber reinforcement be used to allow a larger spacing of control joints than in unreinforced concrete.
2. Since plastics lose their tensile properties at 150 °C, it is recommended that synthetic fiber reinforcement be used in applications where the maximum ambient temperature is limited to the range of 100 to 150 °C.
3. Synthetic fiber reinforcement to be used in concrete that will be subjected to prolonged conditions of high humidity should be composed of alkali-resistant synthetic fibers such as polypropylene or polyethylene.
4. Synthetic fibers should be used to prevent plastic shrinking cracking in placements susceptible to this condition.
5. Research should be continued to develop the uses for synthetic fiber-reinforcing material in concrete, especially in the use of higher contents of synthetic fibers to prevent drying shrinking cracking, and in the susceptibility of synthetic fiber reinforcement to alkaline hydrolysis and consequent reduction in service life of synthetic fiber-reinforced concrete slabs.

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METRIC CONVERSION TABLE

1 gal	=	3.78 l
1 cu yd	=	1.308 m ³
1 in.	=	25.44 m
1 ft	=	0.305 m
1 μ m	=	1×10^6 m
1 psi	=	0.00689 MPa
1 psi	=	0.00000689 GPa
1 lb/in.	=	178.6 g.cm
1 oz	=	28.35 g
1 lb	=	0.453 kg
°C	=	$0.55 \times (°F - 32)$

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